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An advanced technological lightweighted solution for a Body in White

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Abstract

Funded by the EC FP7 Program, EVolution project is using the Pininfarina Nido concept car as a baseline for its activities, with the goal to demonstrate the sustainable production of a full electric 600 kg vehicle (FEV). The project has to be finalized by the end of 2016. The existing Body in White (BiW) has been completely reviewed through a design strategy aiming to reduce the number of parts and using innovative lightweight materials and technologies. The considered Al technologies applied on high performances Al alloys provide the opportunities to obtain components with complex geometries and low thickness, merging different parts into one unique element. Besides, it is possible to process a variable thickness element with a single operation.
A “green sand mold” technique allows co-casted joints among elements produced with different Al manufacturing processes.
The potential cost reduction and process simplification in terms of time and assembly are promising: current state-of-the-art, based on traditional moulds, does not allow these opportunities.
The BiW has been hybridized in certain areas of the underbody with a composite material of the PA family, reinforced with GF. This material has been obtained improving existing ones and developing a production process suitable for scaling to commercial requirements, throughout an advanced sheet thermoforming and 3D-injection method (CaproCAST process).

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Novel polypropylene nanocomposites (PNC) based on silicate and glass fiber layers demonstrate improved toughness and stiffness and have been selected for crash cross beam and side door. Polyurethane foams based on recycled polymers are explored as sustainable energy-absorbing filling in cross beam sections.
Structural epoxy adhesives have been considered to join the BiW parts and welding points are reduced in number: in certain areas spot-welds have been used only to tack the parts during polymerization.
In addition to the previous results, current weight of the BiW is 115 kg versus 160 kg of the baseline car. An FE-analysis on the virtual full vehicle indicates a good structural behavior, considering EU standards of crash homologation and global static and dynamic performances.
The developed architecture and the integration of lightweight materials will ensure that the EU maintains its competitiveness against the Asian and United States automobile industries.
This topic is focused on the results obtained on the BiW in terms of design strategies, Al and composite materials innovative technologies and joining methods.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Lightweight; electric vehicle; aluminium processing; composite; design; Body in White

Nomenclature

ADHSS	Advanced High Strength Steel
BIW	Body in White
EV	Electric Vehicle
FEV	Full Electric Vehicle
ICEV	Internal Combustion Engine Vehicles
OEM	Original Equipment Manufacturer

1. EVolution Project motivations

Lightweight materials have always been an important element in product design, across several industries. The concept has been most important in aviation but also in industries where large rotating parts (e.g., rotor blades of wind turbines) are key elements of product design. The automotive industry has been paying increasing attention to vehicle weight for decades since it has a direct impact on driving dynamics and fuel consumption. Due to the high cost of potential lightweight solutions and consumers’ limited willingness to pay for weight reduction in automotive, the use of costly lightweight materials has been limited so far.

Global trends toward CO_2 reduction and resource efficiency have significantly increased the importance of this matter over the last years; the European Commission sets targets for average new car CO2 emissions of 95 g/km by 2020, and the forecast for 2030 is to reduce emission down to 75 g/km.

These targets cannot be achieved with engine efficiency and lightweight materials alone. Electrified powertrains will have to contribute to a certain extent to this achievement.

Therefore, OEMs will push for electric cars with a resulting increase in system weight and cost (e.g., the cost for bigger batteries, more powerful breaks, and damping systems). Lightweight contents again are needed to reduce the impact of additional system costs for electrification but also for CO_2-optimized internal combustion engines (ICEs).

To reach their CO_2 targets, OEMs can choose between alternatives, like improving the powertrain efficiency (e.g., through improved stop-and-start or downsizing), lightweight materials, or electrification (not necessarily pure battery-electric vehicles, but also hybrids and range extenders).

Concerning fossil fuels, all current battery technologies have a much lower specific energy, which limits Fully Electric Vehicles (FEVs) maximum range.

Consumers worldwide expect FEVs to travel farther, requiring a shorter charge time at a lower retail price.

Thus, while looking for a breakthrough technology leading to a quantum leap in batteries capacities and power-to-weight and energy-to-weight ratios, the weight reduction plays a fundamental role in order to increase the range of FEVs.

To fulfill the need for lighter cars, three different “lightweight packages” are available:

- a significant usage of high-strength steel, using all the potential of steel technology
- a higher employ of lightweight metallic materials, as aluminum, also for Body in White (BiW)[1] parts
- a combination of lightweight metallic materials and composites for structural parts.

The third option, if compared with the first, has relevant costs, especially related to raw materials, but offers a higher weight reduction potential.

Furthermore, the FEVs peculiarities in several areas make necessary to study new specific solutions, while the largest part of FEVs today are simply adapted from ICE vehicles using an existing body, carrying over the same drawbacks of conventional ICE architectures.

Innovative design approaches for FEV should be identified then to reduce product weight (and costs) while keeping the same performances of ICE vehicles as far as safety, comfort and maintenance are concerned: the success of a large-scale introduction of FEVs on the market relies on the conception of a radical new vehicle archetype. In this scenario extreme lightweight packages will become even more relevant over time.

While the passage from lightweight package 1 to 2 is a matter of adaptation (the numerical simulation are ready to go, the forging and forming standards are available and the industrial tool is preserved), the passage from lightweight package 1 to 3 is a revolution, because it implies the creation of conception and validation standards, (where conception has to be intended both on product and process on the perimeter of the vehicle structure), the compatibility of the industrial tooling (fabrication, control, assembling, painting), the reparability and recyclability.

Another important key factor is the bonding technology to be extensively applied in automotive field; without that, modern lightweight designs would hardly be feasible – especially when it comes to bonding dissimilar and/or new materials.

Representing approximately 40% of total vehicle weight, the Body in White (BiW) is the heaviest vehicle element. The consequent implementation of lightweight measures in the car body appears very effective. Increasing demands regarding stiffness, acoustics, crash performance and long-term stability are generally in conflict with lightweight construction and increase the complexity of this challenge.

Currently, BiW different elements are made in stamped metal sheet mainly joined by spot-weld, and have a structural or aesthetical function. This approach is followed for mass production, where high volumes of daily production justify the high investment and requires the highest levels of automation.

Revolutionary concepts have been recently presented to the public disclosing an under-body which plays multiple functions (battery pack protection, structural functions, modularity). Some intents have been made in producing small series of glass fibre architectures (1994 Lotus Elise) presenting several design problems associated with the lack of knowledge and ageing on those materials and manufacturing processes. Another attempt was made by introducing extruded aluminum alloy profiles and adhesives or rivets as the joining techniques (2006 Tesla Roadster) although the manufacturing process and the final cost of such vehicles make them unsuitable for mass introduction. The most significant examples of architectures made in carbon fibres are the new McLaren MP4-12C (monocoque obtained by a unique mould) and the BMW i3 (FE vehicle). Finally, in the US Ford and GM are currently investing resources to substitute a metal sheet underbody, made by 25 assembled elements, with a composite one, made by not more than 5 elements.

These examples reveal some limits since they do not foresee modularity, weight reduction and multi-functionality at the same time.

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[1] Body in White (BiW): It refers to the stage in automotive design or automobile manufacturing in which a car body's sheet metal components have been welded together — but before moving parts (doors, hoods, and deck lids as well as fenders), the motor, chassis sub-assemblies, or trim (glass, seats, upholstery, electronics, etc.) have been added and before painting.

2. EVolution Project goals

EVolution project is based on the Pininfarina Nido concept car. Nido EV takes up, and updates, the lines and volumes that won the Nido of 2004 the award for the Most Beautiful Car in the World in the "prototypes and concept cars category", the Compasso d'Oro 2008 and a place in the temple of modern art, the MoMA of New York.

Nido EV concept is not derived from an ICE vehicle, but it has been conceived directly as FEV. It is a fully electric A-segment city car, featuring 2 + 1 places, 2 doors, and a modular rear end for van version and pick-up versions with high safety standards.

This modularity / flexibility and production technology theoretically allow the development of a product family with different uses and optimized investment & costs to ensure the competitiveness of the product. Business case is based on small series (500-1000 vehicles/year). The layout is a rear wheel drive E-axle with central 22 KWh Li-Ion technology battery.

The chassis is a front Mc Pherson suspension with rear trailing arms.

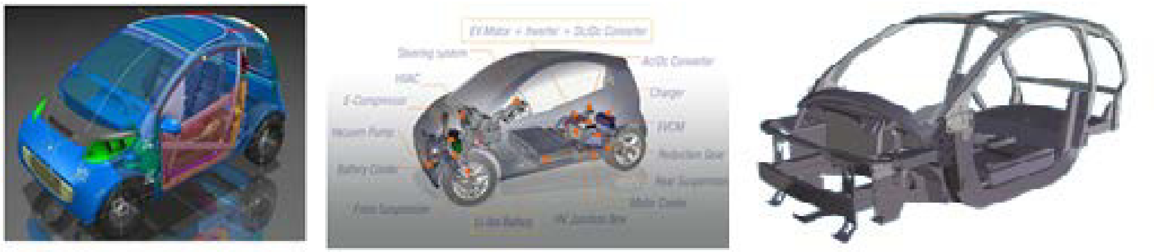


Fig. 1. Current Pininfarina FEV concept - State of the Art.

Current baseline Nido concept is composed by a structural underbody plus a non-structural upper body; the goal of this concept is the design of an Aluminum structure minimizing the casting parts and maximizing the usage of commercial extruded elements: main body sections are obtained by assembling different profiles. Technological consideration apart, this solution appears as cheaper, but the risk is to have a weight increasing even where it is not necessary. Current estimated weight of Nido concept full vehicle is about 850 kg.

3. Activities performed on Nido BiW to conceive EVolution BiW

The baseline concept has been deeply analysed with the purpose to lighten the full vehicle weight from about 850 kg to 600 kg (potential EVolution target).

To catch this goal, two activities have been conducted:

- the Nido concept Bill Of Materials (BOM) analysis, to single out the areas of potential weight reduction with the associated rough mass saving estimation : this has allowed to define a weight target for the BiW, which is the system interested by project analysis;
- the analysis of future trends of components of the traction chain, in particular the battery, with the aim to reduce weight.

As for item 1, having identified a range of light weighted mass for each subsystem starting from respective Nido weights, the BiW weight has been derived as difference between the target full vehicle weight (600 kg) and the sum of the estimated weight of all the other subsystems:

$$\boldsymbol{BiW_{weight} = FullVehicle_{weight} - \sum (Int/ExtTrims, Closures, PWT, Chassis, Suspension, HVAC, SIEE, Cables, Fluids, Std.Elem)_{weight}}$$

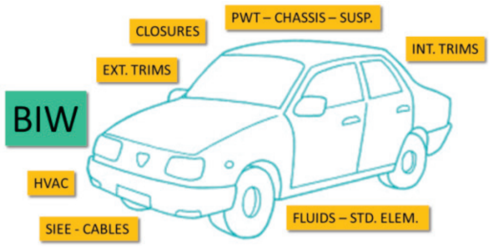


Fig. 2. Vehicle as a sum of systems characterized by a mass.

Resulting weight target range for BiW is 99 – 114.5 kg.

The information derived from these analyses has represented the basis for the complete revision of the baseline BiW, performed by Pininfarina.

The main driver has been: Lightened everywhere, reinforced where is necessary; the approach has taken into account information based on an assessment of mass reduction opportunities for a 2017 – 2020 Model Year Vehicle Program from Lotus Engineering Inc., for The International Council on Clean Transportation, March 2010.

Due to the fact Nido project is still on a concept level, many technological and manufacturing issues have not been solved yet; besides, detailed Computer Aided Engineering (CAE) analysis showed several areas of potential improvement, also working on archetype definition.

Before starting any hybridization activity, it has been necessary to conceive a first release of EVolution BiW characterized by all these items:

- theoretical weight target for EVolution BiW reached (99 ÷ 114.5 kg)
- same Nido style and ergonomic
- main technological issues solved
- weak areas for severe crash and/or body rigidity performances identified by CAE analysis

Starting from the Nido archetype makes it hard to reduce weight down to the theoretical BiW target working only on single parts definitions; there are too many elements which concur in the BiW definition. Among them, some parts have a constant section so there is not an optimized distribution of mass; a reduction of this amount, and a consequent revision of shapes, is deemed necessary.

Looking more in detail to the car, two modalities of decomposition are possible:

- Underbody + Upperbody (Nido)
- Central cell + Front End + Rear End

This second option puts in evidence the modularity, which is one of the EVolution project pillars.

Fig. 3. Nido and EVolution archetype.

A central structural cell has been designed to satisfy body stiffness and crash requirements, especially the side crash, and to support battery. The front end, semi-structural, has been drawn in order to have a controlled folding in a front crash and to support front suspension.

A rear end, semi structural, has been conceived to support the rear suspension and to carry on the specific exterior trim parts which characterize the vehicle version: city car, VAN or pick-up.

The selected body archetype with a central cell is a consolidated standard considering the assembly process scheme, in order to easily shift from low to high production volumes. Basically, the cell has a structural function, while the front end is dimensioned to absorb energy during a front crash and the rear end is conceived to be modular, allowing the transformation into van and pick-up versions.

The starting point has been the generation of an EVolution BiW in the weight target range, completely made in different aluminum alloys, to be theoretically manufactured with innovative aluminium technologies (gas forming, hot forming).

The EVolution BiW and Full Vehicle have been modeled with Finite Elements (FE) methods and evaluated by CAE, simulating the main global behavior in terms of stiffness and crashworthiness.

Weak areas have been singled out, and after a deep problem solving activity, a set of solutions to improve the structure behavior has been put in place with a minor weight increasing.

From this condition, the integration and harmonization of some selected parts into the BiW (in principle, the Demonstrators plus some others nonstructural or semi structural elements) with lightweight materials and innovative technologies have been performed.

Next paragraphs will provide more details on two Demonstrators which are part of the EVolution BiW: the Underbody and the Structural Node.

4. Focus on Underbody demonstrator

The IAM consortium is the partner responsible for the co-design, together with Pininfarina, and the demonstration of the new concept of underbody with integrated battery pack of the EVolution vehicle.

Being IAM Consortium the owner of a set of technological alternatives, its added value has been crucial in term of choices to be made to meet design activities with technological and process requirements in a product development phase.

First activities carried out to redesign the Nido underbody have been:

- Screening of possible product/process/material alternatives to be investigated;
- Selection of the most promising alternatives in terms of weight reduction/costs/production volumes and technological added value;
- Technological macro-feasibility analyses;
- Preliminary experimental tests on existing dies to assess the technological feasibility of a certain production process;
- Support to Pininfarina design activities and consideration.

Two approaches have been considered from the beginning:

- Integrated approach – leveraging new process technologies to merge in a unique new component as much components as possible;
- Single component optimisation – each component is optimised for its function separately from the others.

The combination of the two approaches leads to the maximum potential in weight saving with respect to the Nido underbody.

As result, the very first hybrid structure for the components belonging to the underbody framework of the Nido-EVolution has been evolved to the first EVolution structure. Next image shows the difference at level of underbody from starting point (a) to redesign (b).

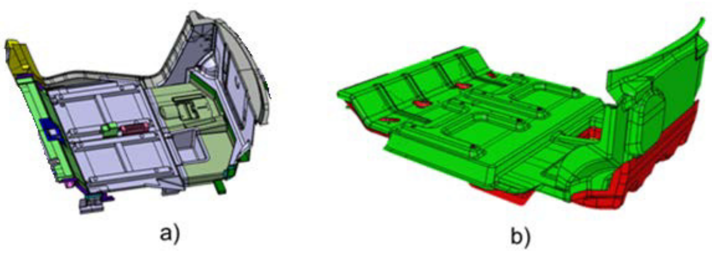


Fig. 4. Nido (a) and first EVolution release (b) of underbody.

Basing on the conceptual work done by technological partners (mainly IAM Consortium and CRF), Pininfarina reengineered the underbody taking into account the constraints of the selected advanced forming technologies and exploiting the weight reduction potential through:

- complex geometry
- integration of different components into one single part
- reduced thickness

The solution presented in the revised design b) allows for a weight reduction of about 20 kg. This weight saving is obtained by considering the total weight of new components and old components eliminated (standard Aluminium).

Final solution of underbody demonstrator has been hybridized supposing high performance aluminium alloys and composite components, with a noticeable variety of innovative manufacturing processes.

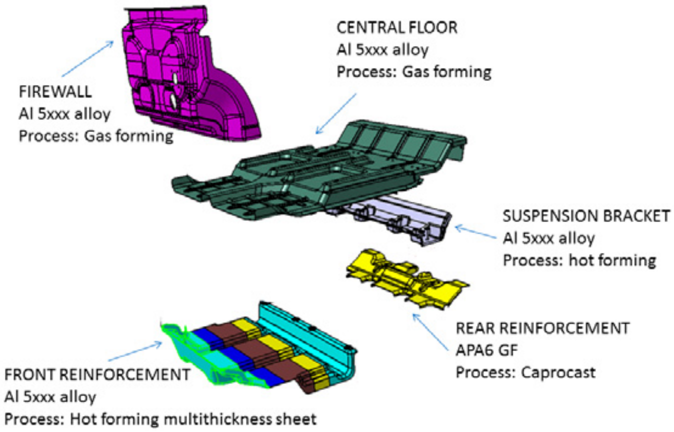


Fig. 5. Final design of EVolution underbody.

Strength points of the current design are:

- To give more freedom to the engineers in the structure optimisation allowing to put material where is needed without compromising cost efficiency;
- Integration of different components into one unique component: for example, the firewall includes also the front part of the central tunnel and part of the wheel-arches;
- Complex geometry and lower thickness enabled by advanced Al technologies (one-step forming process)
- Further mass saving enabled by multi- thickness Al components (front reinforcement)
- Hybrid sub-system which can be treated with e-coating process (rear reinforcement)
- The selected material portfolio offers concrete exploitation potential in a short term perspective since the IAM Consortium includes the complete supply chain: from the material supplier to the final OEM; in a medium/long term further opportunities in terms of weight reduction could arise from the ongoing development of alternative alloys such as new 6xxx and 7xxx alloys, tailored to the new processes;
- Further cost reduction may arise from the usage of secondary aluminium alloys which are increasingly finding interest in the automotive world since combine recycling issues with cost efficiency.

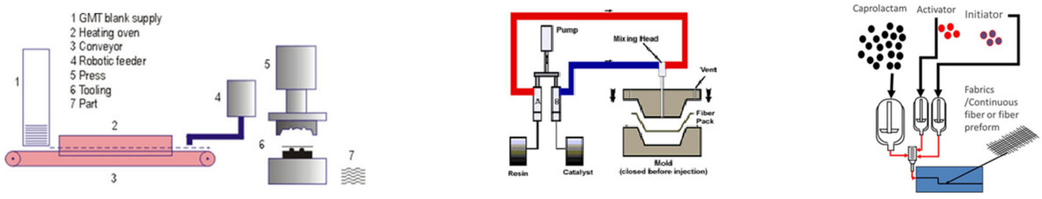
Rear reinforcement material and process have been studied and optimized by Tecnalia.

CAPROlactam CASTing (CAPROCAST) is a reactive process of in-situ polymerization consisting of Polyamide 6 (PA6) casting from its monomer, caprolactam. It is a complex one-step process with a strict control of parameters that have influence during the polymerization and molding; the low viscosity of the casting makes easily to infiltrate the matrix in fabrics and textile preforms. This process is currently used for the manufacturing of preforms as row, tubes or sheet.

Fig. 6. CAPROCAST process compared with injection moulding process.

CAPROCAST process could be an interesting alternative to traditional structural thermoset composites. Respect to compression moulding, this process is less cost effective implying low pressure equipment and cheaper material. Allowed fiber percentage is higher in CAPROCAST (65% vs 50% of compression moulding). The disadvantage is a cycle time of 6-8 min versus 1 min of compression moulding.

Compared with RTM epoxy matrix process, CAPROCAST products are recyclable, weldable and with a good impact resistance, while costs and cycle time are similar.



a) b) c)

Fig. 7. Compression moulding (a), RTM (b) and CAPROCAST process (c) schemes.

The thermoplastic composite selected for EVolution rear floor reinforcement has been improved from existing material system PA. A relevant series of reinforcements has been studied during the project; for this specific underbody element, the best being Glass Fiber (GF) Johns Manville Fabric (Caprolactam sized fabric). A complete characterization has been accomplished on the best manufactured formulations (48% Fibre Volume Content with a fabric balance 80/20). Some tests to evaluate the APA6/CF behaviour to e-coating process have been performed by CRF. Similarly to all the APA6 polymers, APA6/GF is able to survive to e-coating because its melt temperature is above 200 ºC: e-coating is at 180 ºC with peaks up to 190 ºC.

During the treatment, the material reacts with phosphoric acids: the plastic surface becomes white (probably not uniformly), but mechanical characteristics do not change. Painting results are very poor because the paint does not stick, with a possibility of peeling. Basing on these test results, it was concluded that APA6/GF can be used for components that go through e-coating, but without aesthetical requirements, as floor rear reinforcement is.

5. Focus on Structural Node demonstrator

The main purpose of this demonstrator, developed by CIDAUT, is implementing an innovative solution for aluminium components, a co-casted joint between different elements produced with different manufacturing processes.

CIDAUT technology, a green sand mould casting process, provides the media to link different parts when they are placed into a sand mould and then molten aluminium flows around them.

Because of low thermal conductivity of sand, solidification of molten aluminium inside the mould occurs very slowly, which implies microstructures that cannot reach high mechanical properties. Heat treatment process after casting operation could improve that microstructure.

In order to apply this kind of treatment, no pores inside the component are allowed; this is possible only with a counter gravity and controlled filling, avoiding turbulence movements. This filling control is provided by an electromagnetic pump able to transform an electric signal into pressure over the molten aluminium. This device has no delay in response, so sharp changes in filling profile are possible in order to adequate pressure (flow velocity at last) to specific sections.

High thermal conductivity of Al causes that molten metal gets frozen when it is filling the mould; thick sections and silicon addiction help to maintain fluidity. This implies a demonstrator with 5-6 mm section thickness.

Moreover, high productivity rates in an industrial scale demands an automatic casting process, thus the green sand mould is produced with an automatic machine. This characteristic fixed mould dimensions.

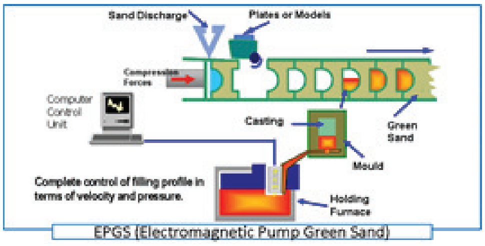


Fig. 8. Cidaut process scheme.

The main advantages for this technology are: cheaper development process, lower tooling cost (cores are easier and cheaper to manufacture versus the standard process) and allows high flexibility in geometry references, complex shaping and hollow geometries.

An unfavorable requirement of this process is minimum thickness limitation and total dimensions fixed by mould size. Low solidification rates mean poor microstructural characteristics, as in traditional sand casting process.

A specific aluminium alloy (A356) has been selected and optimized for this demonstrator. Silicon percentage gives fluidity and high semisolid range (to avoid porosity defects during solidification stage), while magnesium presence makes the alloy heat treatable. Additives like strontium and titanium are used to improved microstructural characteristics. Procedures to these additions have been defined and optimized for this application.

A356 alloy is a well weldable aluminium alloy, so a large component could be manufactured with welded smaller pieces. Thereby, different parts manufactured with various process and aluminium alloys integrate final prototype.

CAE analyses have shown the great influence of the Front Rail Reinforcement both in static and in front crash behavior of the structure. Besides, Front Rails themselves have to be redesigned in shape and thickness to make them collapsible.

The described group represents an important structural area, being the link between the central cell and the deformable front end of the EVolution archetype, so it has been considered suitable to be selected as Demonstrator.

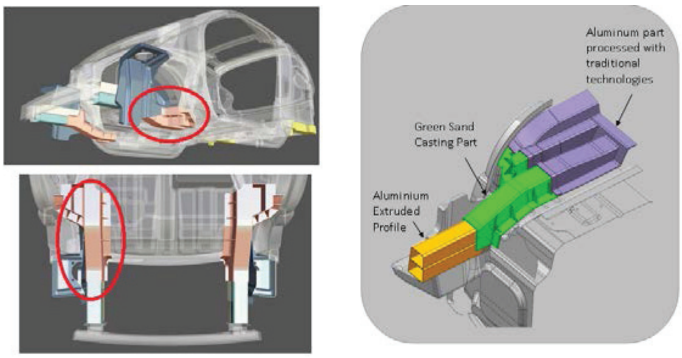


Fig. 9. Structural node demonstrator location in BiW and design details.

6. Focus on interfaces: joining methods

Joining methods have an impact on BiW weight reduction. Adhesives are lighter than spot-welds, so the joining strategy of EVolution has been: "bonding everywhere is possible, welding only where is necessary".

This philosophy has been applied in all the BiW but it has been detailed in correspondence of demonstrators.

In a very theoretical situation, spot-welds (or rivets) could be applied only for tacking the bonded parts to maintain their related positions during the polymerization of the selected adhesives.

In the real conditions, in the area affected by crash, the spot-weld distance cannot be considerably increased, so there will be a continuous bonded line plus a series of redistributed spot-welds. In the area where crash resistance is not a must, the situation will be similar to the ideal one (continuous bonded line plus a tacking series of spot-weld/rivets).

The joining optimization (same as “spot-welds quantity reduction”) has to be performed considering these following missions:

- Front Crash ECE R94 56 kph ODB
- Side Crash ECE R95 50 kph
- Torsional stiffness
- Simplified durability (gravity pavè)

In cooperation with DOW and CRF, the most proper adhesives for the selected interfaces have been selected; they are epoxy based structural adhesives and have been experimentally characterized by partner DOW.

7. Conclusions

After three years of project, EVolution is now entering into the demonstration phase where proof of concept of all the proposed innovations and solutions will be given. EVolution Body in White shows an interesting and promising improvement if compared to the baseline: considering that both structures are conceived in Aluminum, the EVolution one shows a weight reduction of about 45 kg thanks to a smart usage of reinforcements and counterpart reduction enabled by one-step forming technologies.

The obtained architecture is compact and efficient, characterized by innovation from a technological perspective.

The EVolution solution is perfectly aligned with most recent market and regulation trends in the field of FEVs, but also offers interesting hints for the ICEVs market. Several solutions proposed may easily find their application also in high-volume production providing alternative scenario to the one in which ADHSS seems to play their role.

Acknowledgements

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